AFM of nanostructures: growth and fabrication

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A large number of theoretical and experimental studies has been performed over last decade by using a mutual family of instruments, so-called scanning probe microscopes (SPM). Due to recent progress atomic resolution is obtained routinely the both STM and AFM techniques in the case of UHV studies of conductive surface. Remarkable that technological treatments during formation of low-dimensional systems including nanoelectronic device fabrication are not related generally to UHV conditions, for example, gas reaction, ion implantation, various CVD deposition so on. Additionally, technological processes demand rapid structural analysis of the substrate surface. Unfortunately possibilities of SPM are restricted essentially for non-UHV conditions, al least, for reasons mentioned below. First, the tunneling current in STM drastically decreases due to growing natural oxides (dielectric one) on the examined surface. Second, the natural oxidation film covers the surface preventing atomic resolution of surface layer. Third, adsorbed from atmosphere molecules, predominantly water, may introduce artifacts during scan images. Therefore, STM application at ambient conditions seems to be restricted for surface characterization, whereas AFM has to be carefully examined for that. It was the aim of this paper to cover some advantages of atomic force microscopy in the areas of nanostructure diagnostic especially for epitaxial growth technologies and of nanostructure fabrications.

Atomic force microscope, Solver P-47H (NT-MDT, Zelenograd), has been applied to analyse silicon based nanostructures during cleaning, thermal annealing, epitaxy and metal adsorption. The both contact and semi-contact (frequency-modulation) modes were performed at ambient conditions. Standard silicon cantilevers were used with a resonance eigenfrequency of 150÷450 kHz. For stability reasons stiff cantilevers were preferable minimizing the effects of tip-substrate forces. To minimize noise contribution of external electromagnetic fields on the image formation during scanning, the AFM apparatus used for these studies has been placed in side of a metal box having good electric connection to the ground. Additional rubber bearers for this box have been installed reducing mechanical vibration noise. The both temperature and humidity of atmosphere in side of the box were monitoring during AFM scanning.

Some advantages of AFM involvement in epitaxial technology were demonstrated in an application to a silicon substrate. To screen an effect of atomic steps on the surface processes being effective sources for generation and capture of adatoms, we carried out the growth experiments on the “meza”-structured silicon (001) surface. Fig.1 demonstrates the typical topographical AFM-image of the mesa- structured silicon surface. The huge flat areas without atomic steps on silicon surface were formed during thermal annealing or epitaxial growth. Such surfaces were examined in details comparing to atomic process on the stepped silicon surface.

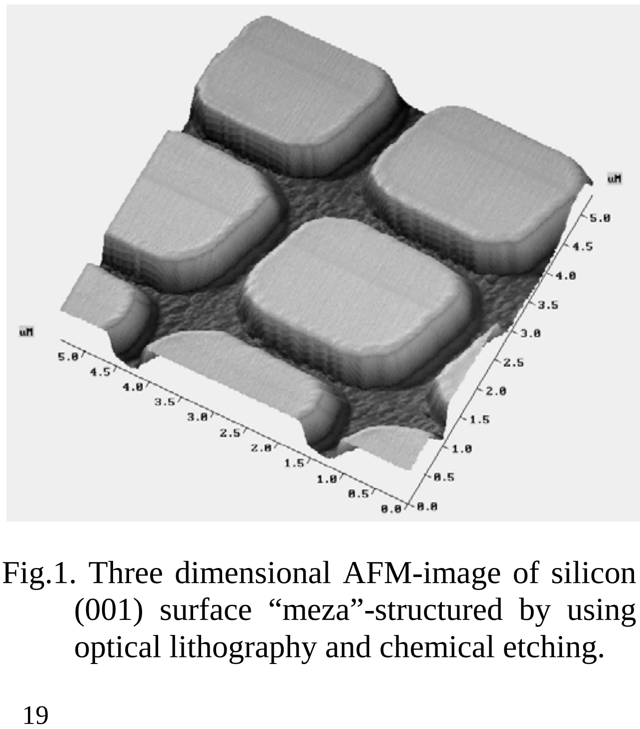
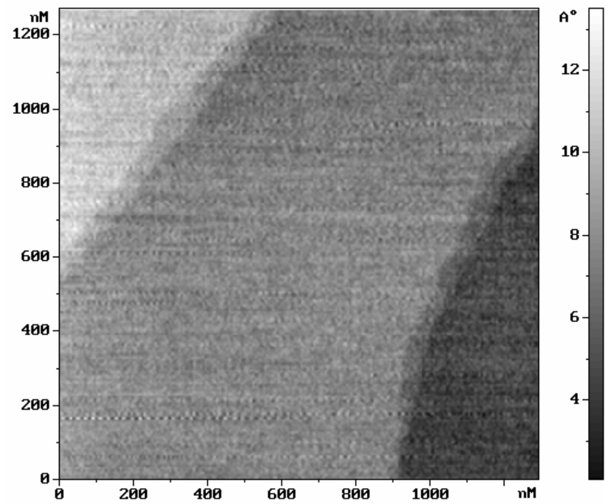
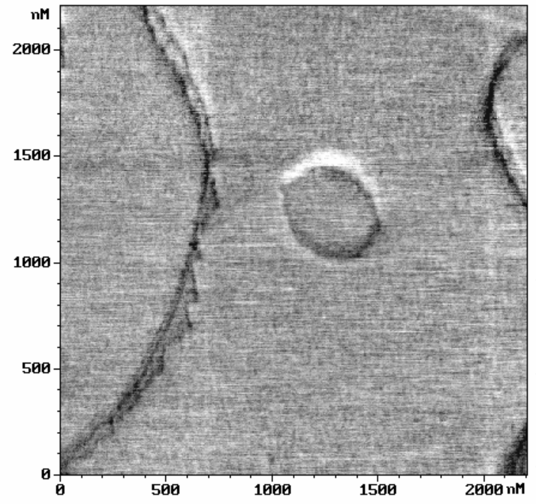


Fig.1. Three dimensional AFM-image of silicon (001) surface “meza”-structured by using optical lithography and chemical etching.





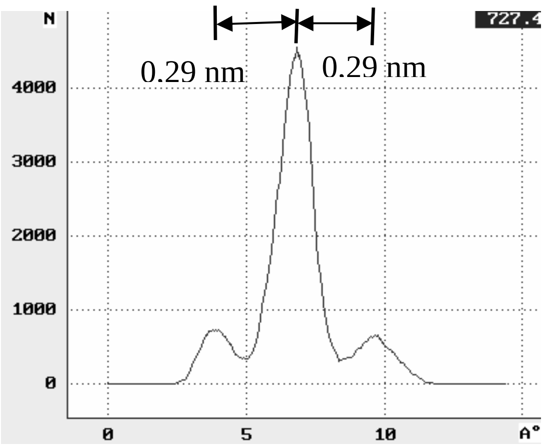


Fig.2. Typical topographic (a) and phase contrast (b) AFM-images of the silicon (001) surface with monatomic steps, 0,14nm in height, which show the step pairing under direct electric current heating. Statistical height spectra from AFM image (a) show clearly three maximum peaks (c). Two-dimensional negative island is shown in (b).

From practice point view the silicon (001) substrate is more used comparison to others orientation. That stimulate us to investigate behavior of monatomic steps on (001) surface during various treatments. Fig.2 demonstrates typical AFM-images of the silicon (001) surface with system of monatomic steps and with negative two-dimensional island which was formed during rapid decreasing of the sample temperature. The coupling steps are shown clearly on Fig.2a. The same phenomenon one can see on the phase imaging (Fig.2b). The height distribution (height spectra) evaluated from statistic analysis of AFM image on Fig.1a shows that height of the step pair is equal to 0,29±0,09 nm. Thus the height spectra is demonstrated evidently that these steps are so-called monatomic steps, in one interlayer height, because the distance between neighboring peaks is measured to be 0,14 nm. Thereby, we can speculate that the natural oxide uniformly replicates the initial stepped surface. As result, the silicon (001) surface may be used for precision calibration of a Z-scanner of AFM in subnanometer scale.

Remarkable that one of the steps in the pair is much rougher due to zig-zag shape that is in a good agreement with free energy calculation for monatomic steps on the silicon (001) surface. Generally step pairing on the silicon (001) surface may be initiated by two effects: surface tension induced by sample deformation [1] and electromigration of adatoms encouraged by DC heating of the sample [2]. The first one has to be ignoring because we minimised a stress sample deformation during construction of sample holder. So far the sample heating was realized by resistively heating of direct electric current through the sample, phenomenon of adatom drift electromigration under has to be calculated. Moreover there was established the changing of the predominated surface reconstruction during changing of the direction of heating current. Peculiarities of structural transformations on the silicon (001) surface have been investigated in details.

AFM method can be successfully used for investigation of nanostructure fabrication by means of epitaxial growth during both homo- and heteroepitaxial processes on stepped surface. Main attention was focused on an investigation of atomic processes during multilayer growth providing roughness of growth boundary and also fabrication of low-dimensional structures driven by self-asembled processes. Fig.3 represents the topographic AFM-images of the silicon (111) surface with two-dimensional islands formed at the second layer after silicon deposition (a) and oxygen etching (b).

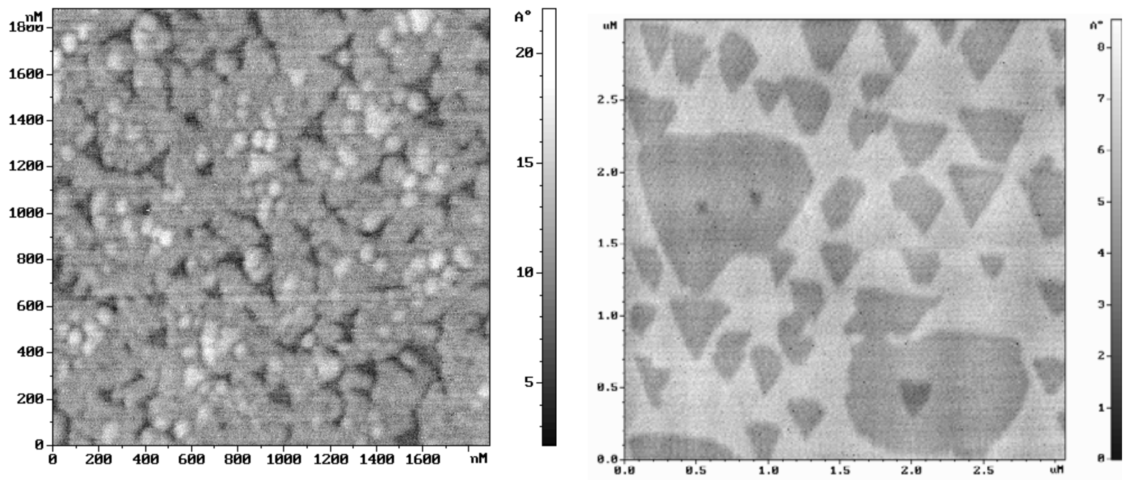


Fig.3. AFM-image of the silicon (111) surface after deposition of silicon atoms (a) and oxygen etching (b) at the condition of multilayer growth.

Instabilities of the step distributions during sublimation, phase transition and growth are under consideration. The transition from the step-flow growth mode to the nucleation of two-dimensional islands has been studied at various deposition rate and substrate temperature. The characteristic growth length described the transition between step-flow and nucleation modes of growth was measure too. Measurements of the critical distance show a strong dependence of the effective activation energy of adatom migration on the atom deposition rate. Precision analysis of island distribution in AFM image was carried out by using “Grain Analysis” software (NT-MDT). The number of parameters characterized the shape, size, form and distribution of islands can be easily derived on the base of the statistical examination.

In conclusion recent AFM applications for growth visualizing, characterization and fabrication of nanostructures are demonstrated for understanding physical and technological background of nanostructures. Atomic force microscopy has been applied to investigate nanostructures including island nucleation and multilayer growth on vicinal and patterning silicon substrates during annealing and epitaxy. Atomistic aspects of SiGe nanostructured formation by molecular beam epitaxy were analyzed. Prospects for nanostructure fabrications based on AFM lithography are shown for nanoelectronics. Thus AFM study provides new opportunities for better understanding growth kinetics on the surface through *ex situ* AFM diagnostic at monolayer resolution.

1. B.S.Swartzentruber, Y.W.Mo, M.b.Webb and M.G.Lagally, J.Vac.Sci.Technol. A.8 (1990) 210.
2. L.V.Litvin, A.B.Krasilnikov and A.V.Latyshev, Surf.Sci.Lett. 244 (1991) L121.